Angel Vilaseca, HB 9 SLV

Microwave Lens Antennas

In order that directivity may be enhanced in the THz range of frequencies, i.e. light!, two properties are used most frequently. These are reflection, as from the surface of a mirror, and refraction, as in a refractor telescope lens. The basic differences in the two properties are shown clearly in figure 1. In the microwave range, by far the most common concentration techniques use the properties of reflection, but there is no reason why refraction cannot be used just in the same manner as it is in optics.

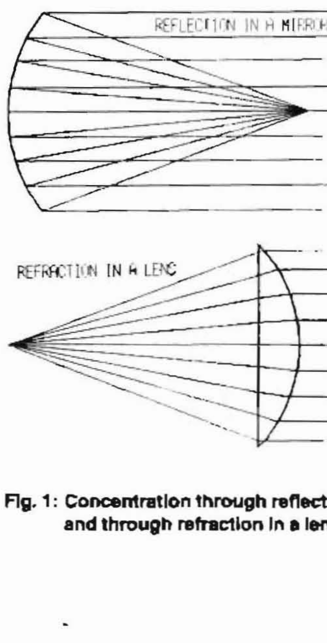

Fig. 1: Concentration through reflection in a mirror and through refraction in a lens

1. SOME BASIC OPTICS

The phenomenon that is usually associated with the property of refraction is caused by the dispersal of electromagnetic waves through media possessing differing densities and therefore at different speeds. In vacuum, the speed of an EM-wave is 300 x 10^6 m/s and through air it is almost same. In other dielectrics, such as optical glass, the speed of light is very much smaller than through air and vacuum and the same applies to dielectrics such as plastics, ceramics, wax etc. All materials have their own characteristic relative permittivities which directly affects the speed of light passing through them. **Table 1** gives a few examples of the relative permittivities ε_r of a few common materials:

Air	1
Polystyrene foam	1
PTFE (Teflon)	2
Wax	2.2
Glass	2 - 5
Ceramic	4.4
Crystal	4.5
Mica	8

Table 1: Relative permittivity of some materials

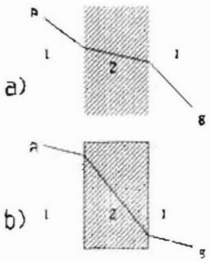

Fig. 2: Every electro magnetic takes the path having the shortest transit time

When a wave passes from point A to point B through two mediums having differing refractive indexes (**fig. 2**), it will always take the path which gives it the shortest transit time. If then, the propagation time through medium 2 is smaller than that through medium 1 (**fig. 2a**), the path length through the medium 2 is minimized. This could be the case if one medium 1 were air and the other medium were, say, glass. If, on the other hand, medium (1) were glass and medium (2) were air, as in (**fig. 2b**), then the EM-wave would be propagated largely through air as it would then be faster.

It is analogous with a situation where one wanted to go from a point A to a point B in the shortest possible time, and that medium 1 is solid ground and medium 2 is water. As one can (normally) walk faster than one can swim, then the route shown in (**fig. 2a**) would be traversed. If the positions of ground and water were transposed, route **2b** would be the natural course to follow.

It could be asked at this stage: why then can't optical lenses be made from wax or ceramic? The answer is, that these two materials are impervious to light, i.e. they have high losses at this wavelength. But what goes for light wavelengths does not necessarily apply to other wavelengths. Both wax and ceramic are excellent for wavelengths corresponding to 10 GHz. Unfortunately, these two materials are not very good to work with and would be very unpracticable as materials for an amateur lens. A better material is polystyrene foam which is very easy to work with and exhibits very low losses. As "sods law" would have it, however, this material has a relative permittivity (ε_r) very close to that of air since it is very largely composed of air. This rules it out for 10 GHz work since a small diameter polystyrene lens would have no influence on the microwaves passing through it. The transit time has not been appreciably altered.

2. METAL-PLATE LENSES

There is a practical means for radio amateurs to fabricate microwave lenses. This makes use of the "metal-plate lens". This is made from this metal plates, cut to a predetermined form, and then placed in parallel juxtaposition at a constant distance from each other. The lens shown in (**fig. 3**) is a possible configuration and is known as the **planar-concave** lens because the virtual outline surface of the combined metal plates is plane on the rear side and concave on the front side as in (**fig. 4**).

It is nevertheless a **spherical** lens since the front face is (almost) a **spheroid**. Actually, this is an over-simplification as it must be an exact **hyperboloid** in order that it can focus the incoming EM-wave to a single point. The difference between the two forms is very small when the diameter of the lens is large in terms of a wavelength. The lens is easier to make if the surface is spherical and if made large enough, it will focus the EM-wave to a point. That is, parallel rays from an extremely distant point source will be converted into a point source and also the reverse is true, a point source at the focal point will be converted to parallel rays of energy.

As may be further seen in figure 3, every plate has its own individual form and size from that of its neighbour. If all plates were identical, then the result would be a **planar-concave cylindrical** lens (**figs. 5 and 6**). In this case, the front surface of the lens is a segment of a cylinder and the

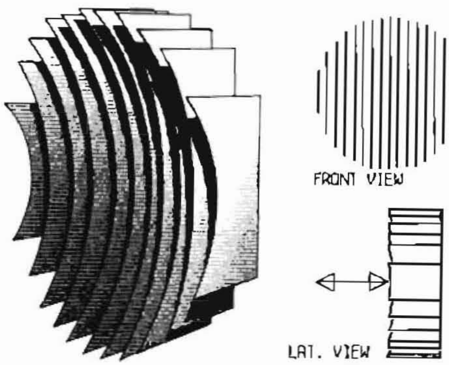

Fig. 3: Three views of a spherical metal-plate lens

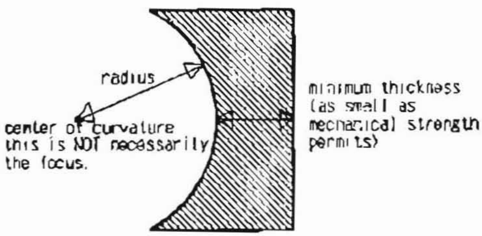

Fig. 4: Form of an elemental metal plate. The focus of radius is not necessarily coincident with lens focus point.

focus is a line parallel to the line that joins all curve centre points.

The lenses shown in figs. 5 and 6 are not equivalent: their insertion loss is dependent upon the polarization of the incident wave – it is at a minimum when the polarization is parallel to the plates.

These metal-plate lenses are known as **acceleration lenses** and represent a basic difference to the classical dielectric lens of the stamp-collector's magnifying glass which delays the incident light waves. When the waves are distributed between the metal elements of a plate lens, they are actually accelerated. Of course, this explanation is necessarily simplified in order to make the comprehension a little easier as it is known, from the theory of relativity, that nothing travels faster than the speed of light.

Following this reasoning, it can be seen that plate lenses have a reversed effect upon waves than that of the dielectric lenses. This means that a concave plate lens has a converging effect and a convex plate lens has a diverging effect. In **fig. 7**, the lens types are shown together for purposes of contrast.

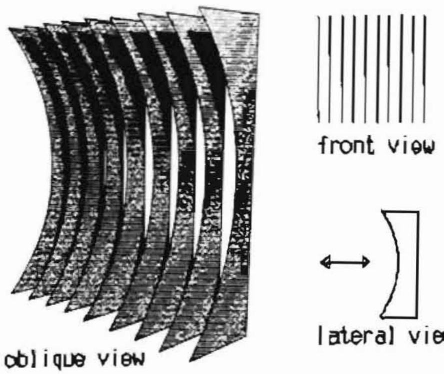

Fig. 5: Three views of a planar-concave, cylindrical metal-plate, vertically-polarized lens.

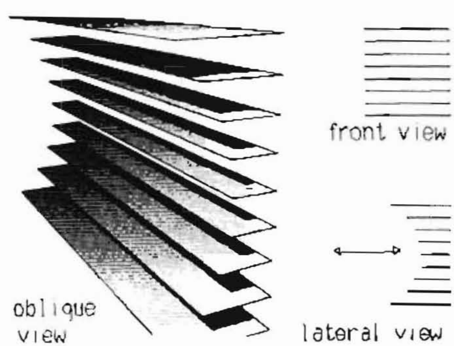

Fig. 6: Three views of a planar-concave, cylindrical metal-plate, horizontally-polarized lens.

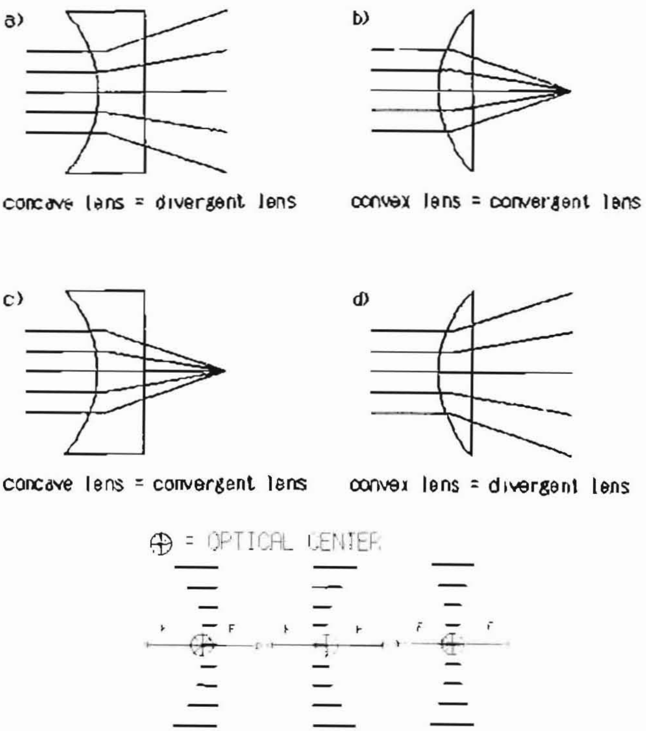

Fig. 7:
Above: dielectric lenses ("delay-lens").
Centre: metal-plate lens ("acceleration-lens").
Below: optical centres,
F = Focus length

A wave which is distributed from the focus point in a ball-shaped wave, becomes a planar wave when it has encountered a spherical concave metal-plate lens (**fig. 7c**). That would be the case for transmission of a wave. If, on the other hand, a planar wave is intercepted by this lens, it is transformed into a spherical wave and concentrated at the focal point of the lens. This is the case for the reception of a wave.

It will be noticed that the lens effect is independent upon direction from which the wave arrives – see **figure 7e**: in both left-hand diagrams the same lens is depicted, one with the waves arriving from the concave side and the other with the waves coming from the convex side. The points at which the waves are concentrated – the focus – is always at the same distance from the **optical centre**. The optical centre is an important point because the focal length is measured from here.

It can be seen in fig. 7e that the optical centre lies on the optical axis – namely in the middle of surfaces of the two lenses, assuming the lenses are symmetrical (bi-concave or bi-convex). With an unsymmetrical lens (plane concave or plane convex), however, the optical centre lies on the optical axis near the lens but the exact location must be determined experimentally.

If the focal point is measured from the optical centre and not from the surface of the lens, then it will be found to be equal on both sides of the lens. The three lenses depicted in fig. 7e have the same focal length and can therefore be considered to be equivalent.

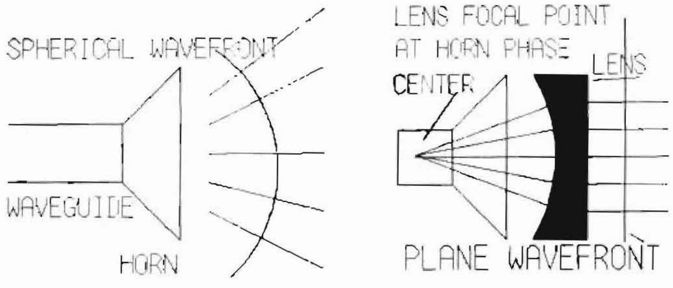

Fig. 8:
Enhancing the directivity of a small horn by using a lens. The divergent beam from the horn is focussed by a suitably placed lens.

The same occurs, incidently, with the concave paraboloid only the waves do not pass through the lens but are reflected from it.

As possible applications for microwave plate lenses, the following are offered: –

* Increase the directivity, and therefore the gain, of a small antenna e.g. a horn, without much of an increase in its overall dimensions (**fig. 8**).
* Optimizing the illumination of any given parabolic reflector and radiator which would otherwise be incompatible with each other (**fig. 9**). This should be of interest to radio amateurs as they often use surplus feed horns and/or parabolic reflectors. A plate lens is much easier to fabricate than a cassegrain sub-reflector to serve the same purpose.

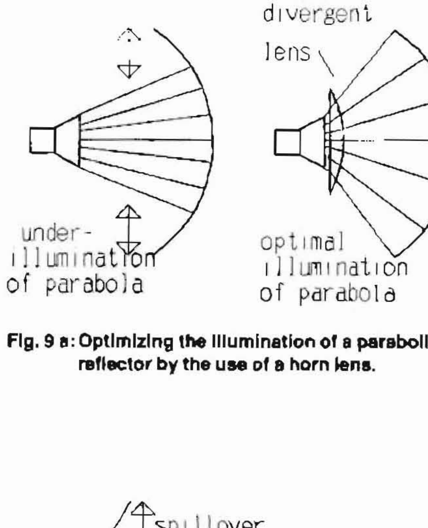

Fig. 9 a: Optimizing the illumination of a parabolic reflector by the use of a horn lens.

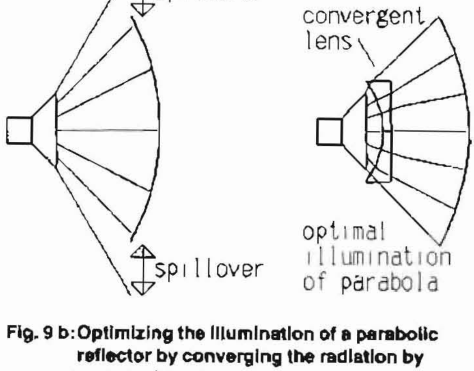

Fig. 9 b: Optimizing the illumination of a parabolic reflector by converging the radiation by means of the lens in order to minimize stray radiation.

3. DIMENSIONING A METAL-PLATE LENS

A lens is characterised by the following dimensions:

1) The focal length
2) The diameter (aperture)
3) The insertion loss

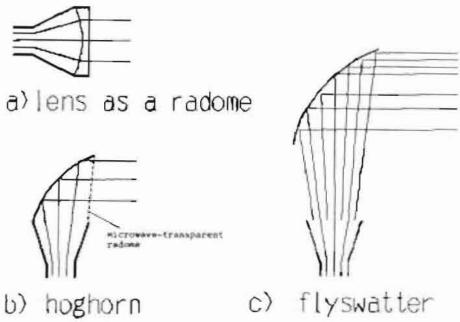

Fig. 10: Three methods of improving the directivity of a horn antenna:
a) lens forms a radome
b) parabolic horn (hoghorn)
c) "flyswatter" antenna

3.1. The Insertion Loss

This depends upon three parameters:

a) The angle between the wave's polarization in the E-plane and the metal plates. The insertion loss is at a minimum when the E-plane lies parallel to the plates.

b) The thickness of the lens

c) The materials used in the construction.

The insertion loss is one of the reasons why this type of lens finds little use in commercial practice. In order to increase the directivity and the gain of horn antennas, there are several possibilities which may be considered. The lens could be located in front of the horn (**fig. 10a**) with a consequent increase in the insertion loss. Alternatively, a hog-horn antenna could be used (**fig. 10b**). This is a combination of a horn and a parabolic reflector which is often employed for terrestrial radio links. The flyswatter antenna (**fig. 10c**) is also in common use.

Another important point concerns both the horn and the reflector (planar or parabolic); they are inherently broad-banded whereas the characteristics of lenses are essentially frequency dependent. Since radio amateurs are usually interested in small frequency ranges, this point is of little consequence. In addition, the fabrication of amateur horn-parabolic antennas is somewhat difficult (5) as the parabolic elemental segments must be quite accurate.

3.2. The Lens Aperture

This is the same dimension as for the combination of both feed horn and lens, and it is that (or slightly larger) of the horn aperture.

A good method is to combine the lens with the horn as shown in fig. 10a. The focal point must lie on the phase centre of the horn – the latter being approximately in the (virtual) apex of the pyramid. In this case, the spherical wave will be refracted by the lens into a plane wave with the focus point being at an infinite distance – its centre being that of the phase centre of the horn.

In the configuration shown in **fig. 11**, the lens serves also as a radome – the space between the lens elements being filled by a material having a low relative permittivity ε_r and low loss, such as polystyrene foam. This keeps the weather from the horn and the wave-guide components – a most useful characteristic. It will be remembered that polystyrene foam does not change the characteristics of the lens.

3.3. The Focal Length

By the help of a little mathematics, the focal length can be determined. As with every lens, the focal length of the metal-plate lens depends upon:

a) The refractive index
b) The curve radius of both front and rear lens surface

The refractive index n is calculated according to formula (1)

$$n = \sqrt{1 - \left(\frac{\lambda}{2d}\right)^2} \qquad (1)$$

where,

λ = free-space wavelength
d = distance between plates

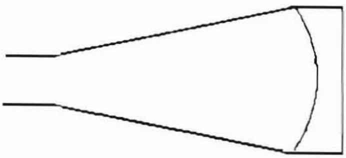

Fig. 11: A physical combination of horn and lens

It can be seen from the formula, that the refractive index n for microwave plate lenses (i.e. acceleration lens) are always smaller than unity. Dielectric lenses, on the other hand, always possess refractive indexes which are greater than one.

Further interesting relationships are as follows:

$$n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} = \sqrt{\varepsilon_r} \qquad (2)$$

where,

ε_0 = Permittivity of a vacuum
= 8.859×10^{-12} Farads per metre

ε = Absolute permittivity of the medium in question

ε_r = Relative permittivity (as in table 1)

Furthermore:

$$n = c/v_o \qquad (3)$$

where,

c = velocity of light in a vacuum (300×10^6 m/s)

v_o = velocity of light in the refractive medium in question

Table 2 gives examples of refractive indexes of metal-plate lenses for three frequencies corresponding to the 3 cm amateur band and five differing spacings d between two plates.

Frequency	10.0 GHz	10.25 GHz	10.5 GHz
d = 18 mm	n = 0.55	n = 0.58	n = 0.61
d = 19 mm	n = 0.61	n = 0.64	n = 0.66
d = 20 mm	n = 0.66	n = 0.68	n = 0.70
d = 23 mm	n = 0.75	n = 0.77	n = 0.78
d = 25 mm	n = 0.80	n = 0.81	n = 0.82

Table 2

Now that the refractive index of the lens is known, the focal length can be calculated using formula (4):

$$\frac{1}{f} = (n-1) \cdot \left(\frac{1}{R1} + \frac{1}{R2}\right) \qquad (4)$$

where,

f = focal length
n = refractive index
R1 and R2 = curve radii of the front or rear surfaces of the lens. A convex surface is expressed by $R > 0$, a concave surface by $R < 0$

The fact that the surfaces are described with curved radii means that they are spheroids whereas a perfect lens would have hyperboloid surfaces. According to (1), they could be provided with one spherical and one hyperbolic surface. In any case, the spheroid represents an approximation which is sufficiently accurate where the radius is not too small. Spheroid lenses are easier both to calculate and to fabricate.

Turning again to formula (4): Assuming that one of the lens surfaces is flat, R2 would represent an infinite radius. Formula (4) may be simplified as follows:

$$\frac{1}{f} = \frac{n-1}{R1}$$

therefore

$$f = \frac{R1}{n-1}$$

therefore

$$R1 = f(n-1) \qquad (5)$$

If it is assumed, on the other hand, that both surfaces are identical and having the same radius, as for example, in a bi-concave lens, formula (4) may be simplified as follows:

$$f = \frac{R1}{2(n-1)}$$

therefore,

$$R1 = 2f(n-1) \quad (6)$$

In order to manufacture lenses to predetermined characteristics, it is recommended to assume a plate spacing of between 19 mm and 25 mm for the 3 cm band. This entails refractive indexes of between 0.61 and 0.80. For the other microwave bands, the spacings can be calculated from formula (1). As it may be seen, the refraction of the lens is inversely proportional to the spacing of the plates. For a given focal length, a relatively large lens radius will have to be given in order that its construction is rendered easier. It must always be remembered, however, that the refractive index must be held within the given boundaries.

4. EXAMPLES

In order to increase the gain of any given horn antenna, a matching plate lens is to be constructed. The 3 cm horn antenna has an aperture of 78 mm x 56 mm and a length of 135 mm (**fig. 12**).

As usual, the horn should be operated in the horizontal plane. For the minimum insertion loss, the plates of the lens are mounted horizontally, as shown in fig. 6. The metal plates are rectangular in form for ease of manufacture – easier than those of figs 3 or 5 for example.

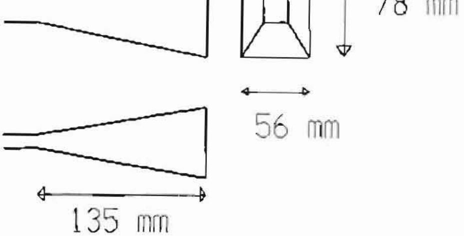

Fig. 12: Horn dimensions for calculation in example

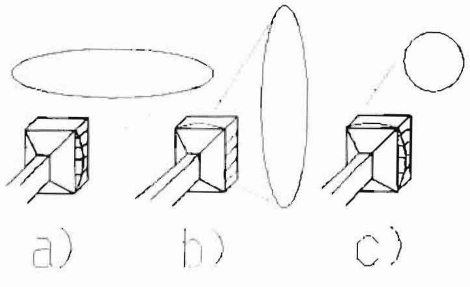

Fig. 13: Three methods of achieving directivity by means of a lens

It is possible to increase the directivity (gain) in either the horizontal plane or the vertical plane by using cylindrical lenses, as in **figs. 13a or 13b**. The directivity may be increased in both planes by the use of a spherical lens as in **fig. 13c**.

The cylindrical lens of fig. 13a is now considered for the first example as this is easier to fabricate than the spherical lens. In the horizontal plane, the lobe is not concentrated and therefore the gain will be lower than with a spherical lens, but still higher than that with the horn alone. In practical transmit operation, this may be advantageous as all the other stations will be on or over the horizon thus making the operational alignment of the antenna less critical. In this arrangement, the valuable microwave energy, which was uselessly radiated into the ground or into the sky, is now concentrated onto the horizon.

The required focal length must now be determined. The phase centre of the horn can be determined in a dimensional drawing: It is approximately 170 mm away from the aperture. Since the lens will be a few centimetres thick, and the focal length is measured from the optical focal point, which lies somewhere inside the lens and on the optical axis, 30 mm must be added to the 170 mm: a lens of 200 mm focal length is required.

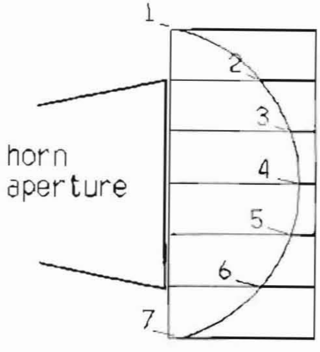

Fig. 14: Lens made with 20 mm thick expanded polystyrene

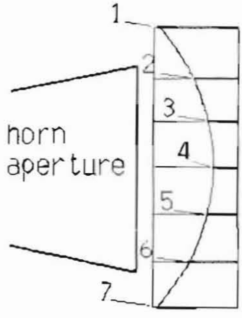

Fig. 15: Lens made with 18 mm thick expanded polystyrene

The lens is made from rectangular plates of aluminium kitchen foil which is about the thinnest metal foil available. The thinner the plates, the less the obstruction they offer to the passage of the microwaves so that the insertion loss is minimized. For mechanical stabilization, the spaces between the foils are filled with polystyrene heat-insulating sheets and glued together. This material is easily obtainable in thicknesses of 20 mm, does not refract microwaves and has little attenuation. The adhesive at 10 GHz, however, can be very lossy and so as little as possible should be used – just enough to keep the assembly in one piece. A glue which does not dissolve polystyrene foam should, of course, be used.

From formula (1), a refractive index of 0.690 can be obtained at 10.368 GHz for this lens.

The radius of the concave surface of the lens is from formula (5), 62 mm.

The plate widths are:

Nos 1 and 7: 58 mm
Nos. 2 and 6: 22 mm
Nos. 3 and 5: 10 mm
No. 4: 7 mm

The length of the metal plates should be 120 mm or more.

Six polystyrene sheets of dimension 65 mm x 120 mm x 20 mm are now required.

Figure 14 shows the lens. Only the bold horizontal lines of the drawing represent the metal foil plates.

If the curve radius appears to be somewhat small, the 18 mm thick polystyrene sheeting should be tried: the refractive index at 10.368 GHz then becomes 0.595 and the radius 81 mm The plate widths then become:

Nos. 1 and 7: 31 mm
Nos. 2 and 6: 19 mm
Nos. 3 and 5: 12 mm
No. 4: 10 mm

The six polystyrene sheets are dimensioned 35 mm x 110 mm x 18 mm. This lens is shown in **fig. 15** and with the small plate spacings, the lens refracts more strongly so that the radius is increased and the lens becomes thinner.

What should be done now if the radius still appears to be too small? The plates cannot be arranged to be any tighter because the minimum recommended refractive index of 0.6 has already been reached.

The lens can be made with a larger radius if it is bi-concave in construction. If both surfaces have the same radius, the previously calculated radius from formula (6) must merely be multiplied by two: that results, using 20 mm polystyrene, in 124 mm and the plate width then becomes

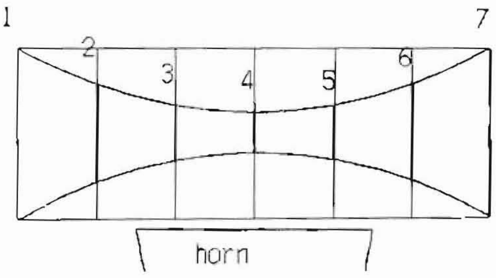

Fig. 16: Bi-concave metal-plate lens:
Radii = 124 mm. Plate spacing = 20 mm

Nos. 1 and 7: 40.5 mm
Nos. 2 and 6: 23.5 mm
Nos. 3 and 5: 13 mm
No. 4: 9 mm

The lens is depicted in **fig. 16**.

If 18 mm polystyrene is used, the radius of both concave surfaces becomes 162 mm.

Should even this rasius be too small, a larger focal length will have to be accepted in order that it can be enlarged. For example 400 mm. Using formula (6), for refractive index of 0.690, a radius for both lens surfaces of 248 mm is obtained (20 mm polystyrene sheeting). This lens is shown in **fig. 17** where it can be seen that the aperture of the lens has been doubled. This influences all microwaves emanating from the horn (or into it). This lens is rather thick.

If a small focal length together with a thin lens is required, a multi-lens system can be adopted as shown in **fig. 18**. The total focal length f is calculated according to formula (7) from the focal lengths of the individual lenses, f1, f2,...fn:

$$1/f = 1/f1 + 1/f2 + 1/f3 + \dots 1/fn \qquad (7)$$

If it is desired that the radiation is beamed in both planes and the gain is then maximized. A bi-concave spherical lens as shown in **fig. 13c** can be used. The metal plates must then have a spacing of 20 mm, a focal length of 200 mm and have a form as depicted in **fig. 19**. This is the bi-concave-spherical version of the bi-concave cylindrical lens as shown in **fig. 16**.

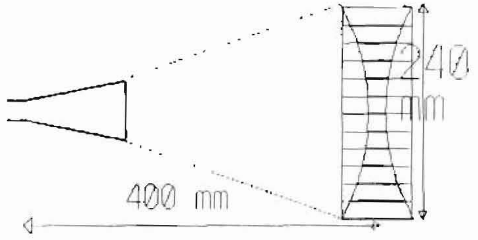

Fig. 17: A 400 mm focal length lens

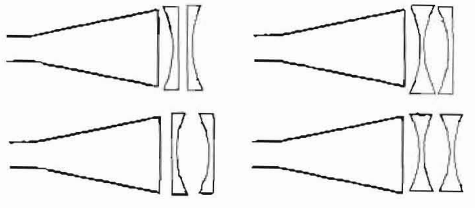

Fig. 18: Various lens combinations

When commissioning this combination of feed horn and lens, only the distance between the horn aperture and lens needs to be adjusted. The highest gain is achieved when the focal point of the lens is coincident with the phase centre of the horn.

For 24 GHz, 10 mm thick polystyrene sheets can be used as distance spacers between the aluminium plates. In this case, the refractive index would amount to approximately 0.78 (It is frequency dependent!).

After these many theoretical considerations, I have resolved to commence the construction and testing of a metal-plate lens, together with other local amateurs, without delay. The results will be published as soon as they become available. I hope that many readers will find the inspiration to build and experiment with this form of antenna!

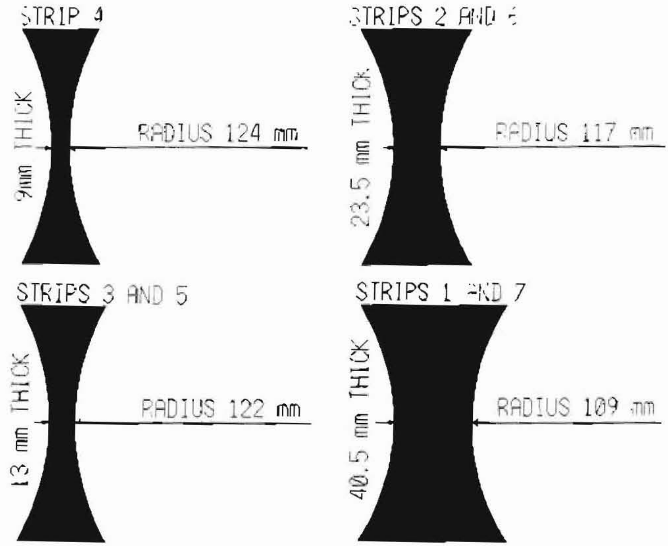

Fig. 19: A spherical convergent metal-plate lens (scale 2 : 1)

5. REFERENCES

(1) Kildal, Jakobsen, Rao: Meniscus-lens-corrected corrugated horn: a compact feed for a Cassegrain antenna. IEE Proceedings, Vol. 131, Pt H, No. 6, December 1984, pages 390 - 394

(2) Clarricoats, Saha: Radiation patterns of a lens-corrected conical scalar horn. Electron. Lett., 1969, 5, pp. 592 - 593

(3) The Handbook of Antenna Design Vol. 1, 1982, ISBN 0-906048-82-6

(4) Reference Data for Radio Engineers Howard W. Sams & Co. Inc. 1981, ISBN 0-672-21218-8

(5) Reithofer, J., DL 6 MH: Praxis der Mikrowellen-Antennen ISBN 3-9801367-0-1 Verlag UKW-BERICHTE, 1987